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**The Use of Ring-Expanded Diamino- and Diamidocarbene Ligands in Copper
Catalysed Azide-Alkyne ‘Click’ Reactions**

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Abstract

The two-coordinate ring-expanded N-heterocyclic carbene copper(I) complexes $[\text{Cu}(\text{RE-NHC})_2]^+$ (RE-NHC = 6-Mes, 7-*o*-Tol, 7-Mes) have been prepared and shown to be effective catalysts under neat conditions for the 1,3-dipolar cycloaddition of alkynes and azides. In contrast, the cationic diamidocarbene analogue, $[\text{Cu}(6\text{-MesDAC})_2]^+$, along with the neutral species $[(6\text{-MesDAC})\text{CuCl}]_2$ and $[(6\text{-MesDAC})_2(\text{CuCl})_3]$, show good activity when the catalysis is performed on-water.

Introduction

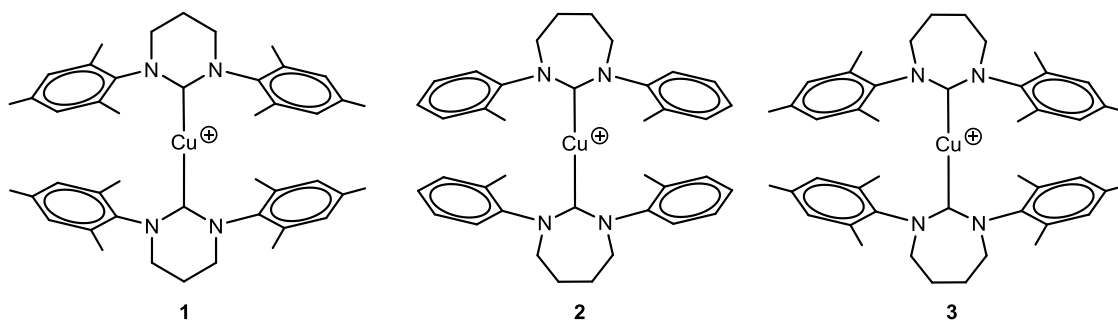
The first copper N-heterocyclic carbene mediated catalytic transformation was only reported a little over a decade ago but,¹ in the intervening time, Cu-NHCs have proven to be powerful tools for a range of catalytic reactions, including hydrosilylation, conjugate addition and carboxylation.² The copper catalysed 1,3-dipolar Huisgen cycloaddition reaction of alkynes and azides has also attracted considerable interest,³ principally because it represents perhaps the best known example of a ‘click reaction’.⁴ Such processes display a number of characteristic properties: they can be easily carried out neat or in a sustainable solvent like water, can be performed without the need for air-sensitive techniques and afford high yields of the desired products with good stereospecificity.

Two general classes of Cu-NHC complexes are used for catalysing this reaction: neutral Cu(NHC)(halide) and cationic [Cu(NHC)₂]⁺ systems.^{3a,3c} In both cases, the presence of very strongly donating, 5-membered ring carbenes affords complexes that display the highest levels of catalytic activity. In the case of [Cu(NHC)₂]⁺ species, this has been rationalised by the need for one of the two NHC ligands to fulfil a secondary function, acting as a base to deprotonate the alkyne. This facilitates the formation of an alkynyl complex Cu(NHC)(C≡CR), which is a generally accepted intermediate on the catalytic pathway.^{3i,5}

With the dual roles of the carbene for both stabilising low-coordinate Cu(I) species and deprotonating the alkyne in mind, we have investigated the activity of a series of new cationic copper complexes (Scheme 1) containing NHCs with >5 ring atoms. These so-called ring-expanded carbenes (RE-NHCs) exhibit considerably

different properties to their 5-membered ring counterparts. Firstly, they feature much wider NCN angles,⁶ which can aid in the stabilisation of low-coordinate metal species.⁷ Moreover, they are also known to be far more basic.⁸ In an effort to try to differentiate the influence of stabilisation vs basicity, we have also looked at the catalytic behavior of similarly sterically demanding, yet less electron-donating, diamidocarbene (DAC) species.⁹

The use of RE-NHCs and DACs in metal catalysed processes is still very much in an embryonic state,^{10,11} particularly in comparison to the ubiquitous 5-membered ring systems.^{2e,12} We report herein that Cu-RE-NHC species with 7-membered rings show improved reactivity over 6-membered ring derivatives, and that in the case of both cationic and neutral Cu-DAC complexes, the presence of the diamidocarbene enhances catalysis performed on-water.



Scheme 1. Ring-expanded $[\text{Cu}(\text{NHC})_2]^+$ complexes

Results and Discussion

Synthesis and Characterisation of $[\text{Cu}(\text{RE-NHC})_2]^+$. The cationic bis-RE-NHC complexes $[\text{Cu}(6\text{-Mes})_2]^+$ (**1**), $[\text{Cu}(7\text{-}o\text{-Tol})_2]^+$ (**2**) and $[\text{Cu}(7\text{-Mes})_2]^+$ (**3**) were readily prepared as the $[\text{BF}_4]^-$ salts upon addition of 2-3 equiv of carbene (prepared in-situ in the

case of 7-*o*-Tol due to base induced side reactions)^{6b} to [Cu(MeCN)₄][BF₄] at room temperature. Complex **1** was reported previously from the reaction of [6-MesH]Br/KO^tBu with CuCl, although this afforded the cation with a mixed [CuBrCl]⁻ anion.¹³ The three complexes were isolated as air-stable solids in yields of 79, 48 and 17% (increased to 25% by performing a 14 h reaction at 50 °C) respectively, the steadily decreasing yield presumably reflecting the difficulty in coordinating two increasingly bulky carbenes onto the copper center.¹⁴

The complexes were characterised by a combination of X-ray crystallography and NMR spectroscopy. The X-ray structures (Figure 1) exhibited the expected linear C_{NHC}-Cu-C_{NHC} geometries for the mesityl substituted complexes **1** and **3** (angles of 178.93(12)° and 179.12(9)° respectively), but a noticeably more acute angle in **2** (173.3(2)°). The Cu-C_{NHC} distances elongate from **1** (1.9266(19) Å) to **3** (1.9540(19)/1.9436(19) Å), presumably as a consequence of the increased repulsion of the N-aryl groups; in accord with this, in all cases the distances were longer than reported in either [Cu(IMes)₂][BF₄] (1.884(2) Å) or [Cu(SIMes)₂][BF₄] (1.896(4) Å).^{15,16} For **2**, the Cu-C_{NHC} distances were 1.905(5) and 1.910(5) Å, shorter than those in **3**.

While the ligand conformations about the metal center can be quantified by the angle between two least squares planes, each containing the carbene-carbon and the two NHC nitrogens from the ligands present (69.7, 89.7 and 88.2° for **1**, **2** and **3**, respectively), this is not especially revealing in itself. Overall, the steric demand of the ligand substituents appears to afford the biggest impact on possible access to the metal center. This variation is illustrated in Figure 2, which shows the access windows in each case. It is clear that, in **2**, entrance to the metal is more easily facilitated due to reduced

steric congestion. Of course, this may have no bearing on solution behavior or catalytic activity (*vide infra*) where either ligand flexibility or ligand dissociation may be relevant.

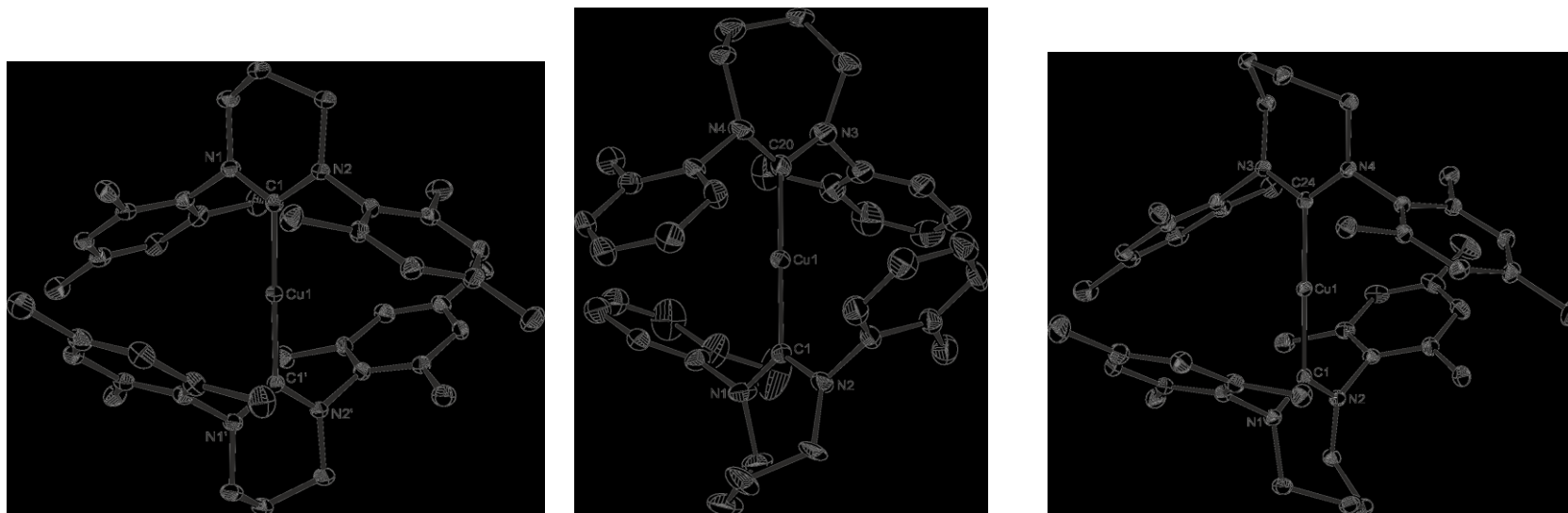


Figure 1. Molecular structures of the cations in (left to right) $[\text{Cu}(\text{6-Mes})_2]^+$ (**1**), $[\text{Cu}(\text{7-}o\text{-Tol})_2]^+$ (**2**) and $[\text{Cu}(\text{7-Mes})_2]^+$ (**3**). Ellipsoids are shown at the 20% level for **2** and 30% level for both **1** and **3**. In **1**, atoms with primed labels arise via the $1 - x, y, \frac{3}{2} - z$ symmetry operation. All hydrogen atoms are removed for clarity. Selected bond lengths (Å) and angles (°) in **1**: Cu(1)-C(1) 1.9266(19), C(1)-Cu(1)-C(1') 178.93(12), N(1)-C(1)-N(2) 117.29(17); **2**: Cu(1)-C(1) 1.910(5), Cu(1)-C(20) 1.905(5), C(1)-Cu(1)-C(20) 173.3(2), N(1)-C(1)-N(2) 118.3(4), N(3)-C(20)-N(4) 117.7(5); **3**: Cu(1)-C(1) 1.9540(19), Cu(1)-C(24) 1.9436(19), C(1)-Cu(1)-C(24) 179.12(9), N(1)-C(1)-N(2) 118.48(17), N(3)-C(24)-N(4) 118.47(17)

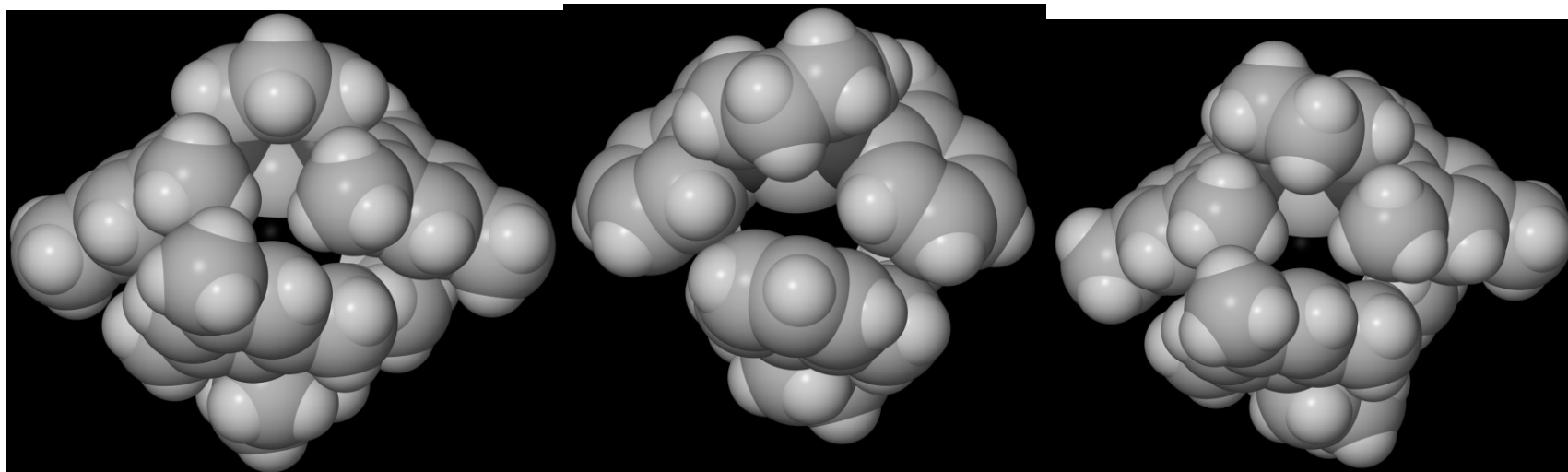
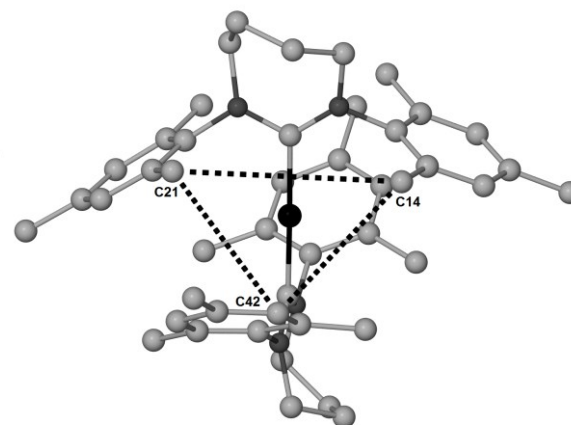
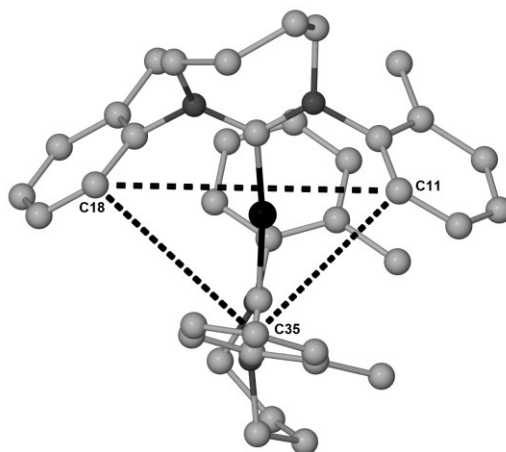
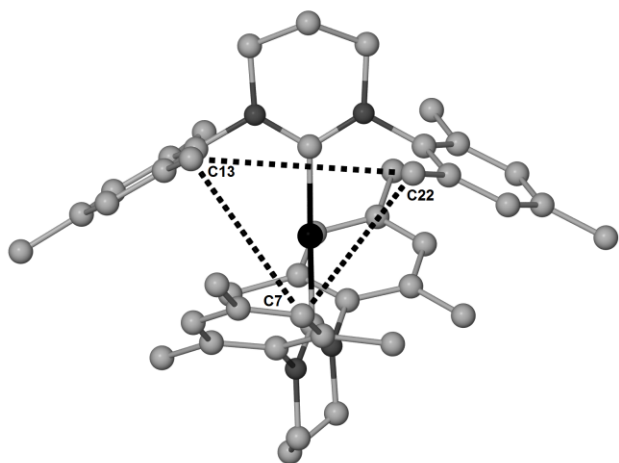
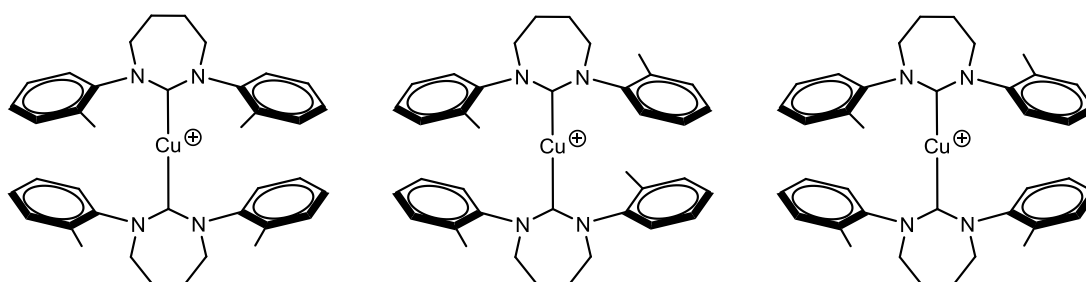


Figure 2. (Upper) Ball and stick representations to illustrate access to the metal centers in **1** (left), **2** (middle) and **3** (right). Hydrogen atoms omitted for clarity. Distances in Å: **1**: C7-C13, 4.18; C7-C22, 3.95; C13-C22, 4.66. **2**: C11-C18, 5.87; C11-C35, 4.23; C18-C35, 4.85. **3**: C14-C21, 5.16; C14-C42, 4.14, C21-C42, 4.09. (Lower) The comparative space filling views, with hydrogens included.

In solution, the previously noted shift to higher frequency of the ^{13}C carbene resonance with increasing ring size was evident in going from **1** (δ 199.3) to **3** (δ 208.6).¹⁷ In the case of **2**, the room temperature $^{13}\text{C}\{^1\text{H}\}$ spectrum was broad, and no carbenic signals could be observed. This broadening appears to be a consequence of rotamers being present in solution, most likely resulting from different orientations of the tolyl Me substituents ; some of these are shown in Scheme 2. Thus, the ^1H NMR spectrum at 298 K showed four, broad overlapping methyl signals, which resolved to five much sharper, but still overlapping signals, at 224 K. At this temperature, the $^{13}\text{C}\{^1\text{H}\}$ NMR spectrum contained eight methyl signals; one major carbene resonance was now apparent at δ 207.2, along with a smaller signal (ca. 1/6 intensity) at δ 206.6 (see ESI).

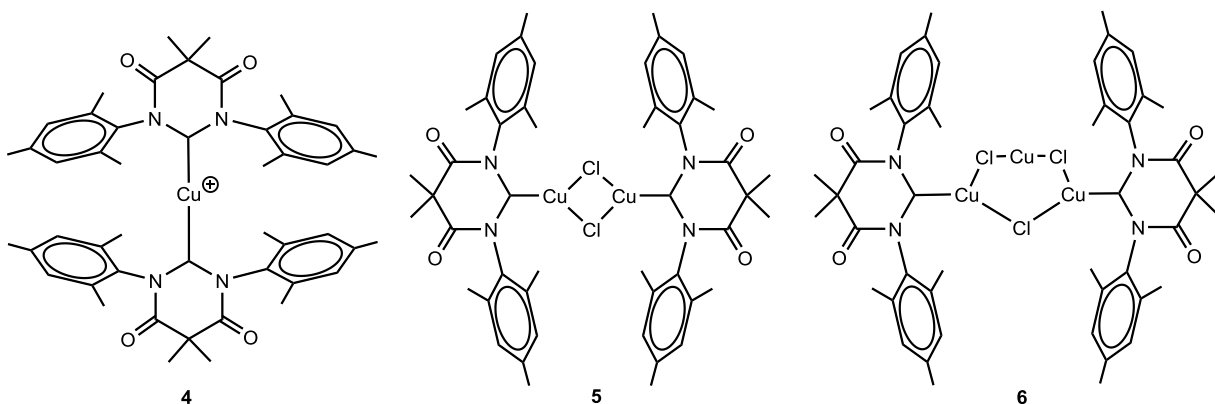


Scheme 2. Examples of rotameric forms of **2** in solution

Catalysis with RE-NHC and DAC Copper Complexes. The catalytic activity of the RE-NHC complexes **1-3** was compared using a test cycloaddition reaction of benzyl azide and $\text{PhC}\equiv\text{CH}$ at room temperature with 2 mol% copper complex. All three complexes gave quantitative conversions to the triazole under neat conditions over 3 h (Table 1). Lowering the catalyst loading (0.5 mol%) and shortening the reaction time to 45 min allowed the relative activities of the complexes to be established, the 7-*o*-Tol

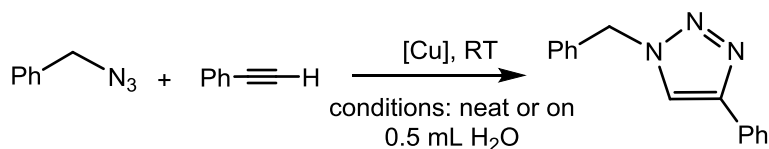
species **2** emerging as by far the most active system with 98% conversion to the triazole.¹⁸ At 0.1 mol%, this complex afforded a conversion of 58% in 45 min.

When the reactions were run on 0.5 mL water, both of the 7-NHC species **2** and **3** were again more active than 6-Mes complex **1**, although the relative ordering of **2** and **3** was now reversed. **2** showed no activity at all in CHCl₃, however, quantitative conversion was found in MeCN, albeit very slowly, over a period of 3 days.



Scheme 3. Range of Cu(6-MesDAC) complexes employed in catalysis

In contrast to the RE-NHC complexes **1-3**, the tetrafluoroborate salt of the DAC complex $[\text{Cu}(\text{6-MesDAC})_2]^+$ (**4**, Scheme 3)¹⁹ was inactive under neat conditions (as well as in both MeCN and CHCl₃). However, changing to on-water conditions, afforded 95% conversion over 3 h at 2 mol% loading (Table 1).²⁰ This accelerating effect from the use of water led us to investigate the activity of the recently reported neutral Cu-DAC complexes, the dimer **5** and trimer **6**.¹⁹ In both cases, conversions of <5% were found neat, whereas quantitative conversions to product were observed on-water. We are unaware of any other cases of Cu-NHC catalysts for this reaction in which the influence of water is so apparent.

Table 1. Catalyst screening.^a

Complex	% conversion neat	% conversion on-water
1	98 (18)	58
2	100 (98)	76
3	>99 (59)	>99
4	<1	95 (8)
5	2	100 (13)
6	5	100 (30)

^a Conditions: Azide (0.50 mmol), alkyne (0.51 mmol), Cu precursor (2 mol%), 180 min.

Conditions for results in parentheses: Azide (0.50 mmol), alkyne (0.51 mmol), Cu precursor (0.5 mol%), 45 min. Conversions determined by ¹H NMR spectroscopy, average of 3 runs.

In light of their effectiveness under quite different conditions, the activity of **2** and **6** towards a range of alkynes with benzyl- and hexylazide was tested under neat and on-water conditions respectively at 0.5 mol% loading and 45 min reaction time (Scheme 4). Although conversions were largely found to be poor in most cases under these conditions, two results stand out: the particular effectiveness of **2** towards $\text{PhC}\equiv\text{CH}$ and either azide, and the extremely high reactivity of **6** for $\text{Me}_2\text{NCH}_2\text{C}\equiv\text{CH}$.²¹ The catalytic conditions were chosen to allow relative performances to be discriminated, and no attempts were made to optimise conversions by running reactions for longer. However, better

carbene is presumed to act as a base towards $\text{RC}\equiv\text{CH}$, although the resultant conjugate acid of 6-MesDAC, which would be formed in such a step, is known to be extremely sensitive to water.²² In the case of the neutral complexes **5** and **6**, we have established¹⁹ that they most likely stay intact as the dimer and trimer in solution; given that a dinuclear Cu species is now thought to be catalytically important,⁵ could this account for their good performance? A wider point relates to whether the DAC complexes benefit from a stabilising hydrophilic interaction to the amido carbonyl groups, which might aid the on-water catalysis. Whether metal DAC complexes exhibit useful catalytic properties in other reactions in which water is a desirable or acceptable solvent remains to be established.

Experimental

All syntheses were carried out using standard Schlenk, high vacuum and glovebox techniques using dried and degassed solvents. NMR spectra were recorded at 298 K (unless otherwise stated) on a Bruker Avance 500 MHz or 400 MHz NMR spectrometer and referenced to residual solvent signals for ^1H and ^{13}C spectra as follows: CD_2Cl_2 (δ 5.32, 53.8), CDCl_3 (δ 7.26, 77.2) and CD_3CN (δ 1.94, 1.3). IR data were recorded on a Nicolet Nexus spectrometer in KBr. Elemental analyses were performed by the Elemental Analysis Service, London Metropolitan University, London, UK or Elemental Microanalysis Ltd, Okehampton, Devon, UK. Literature methods were used to prepare 6-Mes,^{6a} 7-Mes,^{6a} 6-MesDAC,^{9d} [7-*o*-TolH][BF_4],^{6b} [(6-MesDAC)(CuCl)]₂¹⁹ and [(6-MesDAC)₂(CuCl)]₃.¹⁹

[Cu(6-Mes)₂][BF₄] (1). A benzene solution (15 mL) of 6-Mes (0.180 g, 0.562 mmol) was added to [Cu(MeCN)₄][BF₄] (0.059 g, 0.187 mmol) and stirred for 30 min to

afford a colorless precipitate, which was isolated by filtration, washed with benzene (3 x 10 mL) and hexane (2 x 10 mL) and dried under vacuum. Yield: 0.117 g (79%). Single crystals suitable for X-ray diffraction analysis were grown from CH₂Cl₂/hexane. ¹H NMR (CD₂Cl₂, 500 MHz): δ 6.94 (8H, s, *m*-ArH), 3.06 (8H, t, ³*J*_{HH} = 5.8 Hz, NCH₂), 2.35 (12H, s, *p*-ArCH₃), 2.04 (4H, m, NCH₂CH₂), 1.75 (24H, s, *o*-ArCH₃). ¹³C{¹H} NMR (CD₂Cl₂, 126 MHz): δ 199.3 (s, NCN), 141.9 (s, *i*-Ar), 138.6 (s, *p*-Ar), 135.3 (s, *o*-Ar), 130.2 (s, *m*-Ar), 44.6 (s, NCH₂), 21.2 (s, *p*-ArCH₃), 20.7 (s, NCH₂CH₂), 18.1 (s, *o*-ArCH₃). Anal. Found (calcd for C₄₄H₅₆BN₄F₄Cu): C 66.65 (66.79), H 6.99 (7.13), N 7.17 (7.08).

[Cu(7-*o*-Tol)₂][BF₄] (2). A solution of KHMDS (0.538 g, 2.697 mmol) in THF (20 mL) was added to [7-*o*-TolH][BF₄] (0.906 g, 2.473 mmol) and the suspension stirred for 30 min, yielding a bright green solution and white precipitate. This mixture was transferred by cannula to [Cu(MeCN)₄][BF₄] (0.390 g, 1.240 mmol) and the suspension stirred for a further 16 h. The resultant white powder was isolated by filtration and washed with THF (2 x 10 mL). From this powder, the product was extracted into CH₂Cl₂ (3 x 15 mL) and filtered. The volatiles were removed under reduced pressure and the product dried in vacuo. Yield: 0.418 g (48 %). Single crystals suitable for X-ray diffraction analysis were grown from CH₂Cl₂/hexane. ¹H NMR (CD₂Cl₂, 400 MHz): δ 7.47-6.37 (16H, br, ArH), 3.99-3.31 (8H, br, NCH₂), 2.40-1.76 (20H, br, NCH₂CH₂ + *o*-ArCH₃). ¹H NMR (CD₂Cl₂, 400 MHz, 224 K): δ 7.44-6.31 (16H, m, ArH), 3.91-3.30 (8H, m, NCH₂), 2.37-1.69 (20H, m, NCH₂CH₂ + *o*-ArCH₃). ¹³C{¹H} NMR (CD₂Cl₂, 100 MHz, 224 K):* δ 207.2 (s, NCN), 206.6 (s, NCN), 147.4, 147.3, 147.1, 147.0, 146.8, 146.6 (all quaternary Ar), 135.0, 134.8, 134.5, 134.4, 134.3 (all quaternary Ar), 131.4,

131.3, 131.1 (all ArH), 128.8, 128.3, 128.2, 128.1, 128.0, 127.7, 127.6, 127.1, 127.0 (all ArH), 53.0, 52.8, 52.7, 52.5 (all NCH₂), 25.1, 25.0, 24.7 (all NCH₂CH₂), 18.9, 18.5, 18.4, 18.3, 18.1, 18.0 (all *o*-ArCH₃). *C/CH/CH₂/CH₃ assignments based on ¹³C{¹H} PENDANT. Anal. Found (calcd for C₃₈H₄₄BN₄F₄Cu): C 64.32 (64.54), H 6.25 (6.27), N 7.92 (7.92).

[Cu(7-Mes)₂][BF₄] (3). To a mixture of 7-Mes (0.300 g, 0.897 mmol) and [Cu(MeCN)₄][BF₄] (0.137 g, 0.436 mmol) was added THF (10 mL). The reaction mixture was heated at 50 °C for 14 h, to generate a colorless precipitate. The THF solution was concentrated and the precipitate isolated by filtration. It was washed with hexane (3 x 10 mL) and dried in vacuo to afford 0.079 g of **3** (25 % yield). Single crystals suitable for X-ray diffraction analysis were grown from CH₂Cl₂/hexane. ¹H NMR (CD₂Cl₂, 500 MHz): δ 6.93 (8H, s, *m*-ArH), 3.55 (8H, m, NCH₂), 2.36 (12H, s, *p*-ArCH₃), 2.00 (8H, m, NCH₂CH₂), 1.82 (24H, s, *o*-ArCH₃). ¹³C{¹H} NMR (CD₂Cl₂, 126 MHz): δ 208.6 (s, NCN), 144.1 (s, *i*-Ar), 138.3 (s, *p*-Ar), 135.0 (s, *o*-Ar), 130.4 (s, *m*-Ar), 53.6 (s, NCH₂), 25.5 (s, NCH₂CH₂), 21.2 (s, *p*-ArCH₃), 19.0 (s, *o*-ArCH₃). Anal. Found (calcd for C₄₆H₆₀BN₄F₄Cu): C 67.32 (67.43), H 7.42 (7.38), N 6.77 (6.84).

[Cu(6-MesDAC)₂][BF₄] (4). A mixture of 6-MesDAC (0.419 g, 1.11 mmol) and [Cu(MeCN)₄][BF₄] (0.173 g, 0.55 mmol) was stirred in CH₂Cl₂ (20 mL) for 30 min. Volatiles were removed under reduced pressure yielding a yellow/green solid, which was subsequently washed with THF (2 x 15 mL) and filtered. The resulting green solid was dissolved in the minimum amount of CH₂Cl₂ and precipitated with hexane. The solid was then further washed with hexane (20 mL) and dried under vacuum. Yield: 0.376 g (76%). ¹H NMR (CD₂Cl₂, 500 MHz): δ 7.10 (8H, s, *m*-ArH), 2.43 (12H, s, *p*-ArCH₃), 1.71 (24H,

s, *o*-ArCH₃), 1.61 (12H, s, C(CH₃)₂). ¹³C{¹H} NMR (CD₂Cl₂, 126 MHz): δ 212.7 (s, NCN), 170.8 (s, CO), 141.8 (s, *p*-Ar), 135.1 (s, *o*-Ar), 134.6 (s, *i*-Ar), 130.8 (s, *m*-Ar), 52.3 (s, C(CH₃)₂), 24.8 (s, C(CH₃)₂), 21.3 (s, *p*-ArCH₃), 18.6 (s, *o*-ArCH₃). IR (cm⁻¹): 1768 (ν_{CO}), 1738 (ν_{CO}). Anal. Found (calcd for C₄₈H₅₆BN₄O₄F₄Cu): C 63.80 (63.82), H 6.24 (6.25), N 6.13 (6.20).

General catalytic procedure. All catalyses were conducted in air, with no purification of reagents. Into a 2 mL sample vial was weighed 0.01 mmol (2.0 mol%) or 0.0025 mmol (0.5 mol%) of copper complex. H₂O (0.50 mL) was added if the reaction was to be conducted on water. Alkyne (0.51 mmol) and then azide (0.50 mmol) were added by microsyringe, the vial sealed and secured to an agitator set to 2000 rpm. After the appropriate reaction time (45 or 180 min), the contents of the vial were extracted with CDCl₃ (3 x 0.35 mL) and NMR spectra recorded. Products were assigned by comparison to literature data.²³ Conversions represent the ratio of triazole to unreacted azide, as an average of three separate experiments.

X-ray crystallography. Single crystals of **1**, **2**, and **3** were analysed using a Nonius Kappa CCD diffractometer. Data were collected at 150 K and using Mo(Kα) radiation throughout. Details of the data collections, solutions and refinements are given in Table S1 (see ESI). The structures were solved using SHELXS-97²⁴ and refined using full-matrix least squares in SHELXL-97.²⁴

The asymmetric unit in **1** was seen to comprise of half of a cationic copper complex and half of a tetrafluoroborate anion. The copper and boron atoms are coincident with a crystallographic 2-fold rotation axis which serves to generate the remainder of each moiety. The fluorine atoms in the anion are severely disordered. These were

ultimately modelled as six fractional occupancy halides after several alternative elaborate models were discarded. The ADPs pertaining to the boron centre also suggest some positional disorder, which could not be modelled sensibly. B-F distances in the anion were refined subject to being similar and ADP restraints were included for the fractional-occupancy fluorine atoms in the final least-squares, in order to assist convergence.

The diffraction data for **2** exhibited a sharp fall-off in intensity at Bragg angles above 20°. Consequently, the data were truncated to a maximum 2θ value of 50° during the final least-squares refinement. Declining higher-angle intensities reflect, in part, structural disorder which has been modelled. In particular, atoms C2-C5 and C21-C24 exhibit positional disorder in a 65:35 ratio, over two sites. The fluorine atoms in the anion have also been treated as each being evenly split over two sites. This is an approximation, as there is evidence for additional smearing of the electron density in the tetrafluoroborate region of the electron density map. N-C, C-C, B-F and F...F distances pertaining to fractional occupancy atoms have been restrained to assist convergence. ADP restraints have also been applied to the disordered atoms in **2**. In addition to one cation and one anion, the asymmetric unit in **3** was seen to contain one molecule of dichloromethane.

Crystallographic data for compounds **1-3** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publications CCDC 1000555-1000557. Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax(+44) 1223 336033, e-mail: deposit@ccdc.cam.ac.uk].

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Supporting Information Available: VT NMR spectra of **2**, CIF files with crystallographic data for **1-3**, Table S1, references to ¹H NMR data of triazoles. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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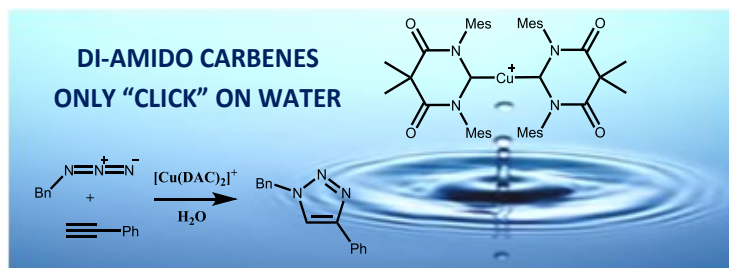
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21. At 0.1 mol% loading, 100% conversion was achieved in 45 min.
22. $[\text{6-MesDACH}]^+$ has been shown to be too electrophilic to occur as the chloride salt, $[\text{6-MesDACH}]\text{Cl}$, instead existing as 6-MesDAC(H)Cl .^{9b} This reacts instantly with water to form 6-MesDAC(H)OH .^{9d}
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The Use of Ring-Expanded Diamino- and Diamidocarbene Ligands for Copper Catalysed Azide-Alkyne ‘Click’ Reactions

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Cationic copper complexes bearing 6- and 7-membered ring N-heterocyclic carbenes, along with cationic and neutral diamidocarbene species, have been employed for the 1,3-dipolar Huisgen cycloaddition reaction of alkynes and azides under neat and on-water conditions. The DAC species show marked enhancement of activity when used on-water.